AD-A233 109

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

DTIC FILE COPY

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE: March 1991

3. REPORT TYPE AND DATES COVERED: 6/15/89-12/15/89

4. TITLE AND SUBTITLE: Advanced Technology for Improved Quantum Device Properties Using Highly Strained Materials

5. FUNDING NUMBERS: PE 61153N; R&T 414s 001-02

6. AUTHOR(S): William J. Schaff, S.D. Offsey and Lester F. Eastman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES): Cornell University, School of Electrical Engineering, Phillips Hall, Ithaca, New York 14853-5401

8. PERFORMING ORGANIZATION REPORT NUMBER: N00014-89-J-1386

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES): Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217-500

10. SPONSORING/MONITORING AGENCY REPORT NUMBER: 1114 ss

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT: Approved for public release

12b. DISTRIBUTION CODE: N00179

13. ABSTRACT (Maximum 200 words)

Strained layer GaInAs/GaAs heterostructures for improved high frequency high performance as a result of strained modified valence band structure continue to be investigated. The first demonstration of improved microwave frequency bandwidths arose from increased differential gain for single strained quantum well structures. Optimized single quantum well growth is therefore undertaken to initiate the development of multiple quantum well lasers in 1990 to further increase differential gain. Properties of strained GaInAs on InP have also been studied. A first attempt to grow and fabricate a laser on InP has been successful, thus opening the opportunity to investigate strained lasers on InP. A first look into the theoretical properties of strained quantum wells has begun.

14. SUBJECT TERMS: quantum wellls, strained layers

15. NUMBER OF PAGES: 33

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
- - - -	- - - -	- - - - - - -	- - - - - -

91 3 26 080

OFFICE OF NAVAL RESEARCH

TECHNICAL REPORT

ADVANCED TECHNOLOGY FOR IMPROVED QUANTUM DEVICE PROPERTIES USING HIGHLY STRAINED MATERIALS

GRANT NUMBER:

N00014-89-J-1386

FOR THE PERIOD

JUNE 15,1989 TO DECEMBER 15, 1989

CORNELL UNIVERSITY

ITHACA, NY 14853-5401

PREPARED BY:

W.J. Schaff

S.D. Offsey

L.F. Eastman

Table of Contents

ADVANCED TECHNOLOGY FOR IMPROVED QUANTUM DEVICE PROPERTIES USING HIGHLY STRAINED MATERIALS

Introduction

Strained layer GaInAs/GaAs heterostructures for improved high frequency high performance as a result of strained modified valence band structure continue to be investigated. In the first half year of research, a new laser structure had been successfully developed which permitted direct high frequency modulation of non wire-bonded lasers. The first demonstration of improved microwave frequency bandwidths for lasers had been achieved. Substantial improvement in bandwidth for strained GaInAs quantum well graded index separate confinement heterostructure lasers over unstrained GaAs quantum well lasers has been measured, accompanied by a reduction in threshold current densities for lasing. Improved bandwidths arose from increased differential gain for single strained quantum well structures. Optimized single quantum well growth is therefore undertaken to initiate the development of multiple quantum well lasers in 1990 to further increase differential gain.

In the second half year of effort (the period of this report) concentration has been on the materials properties of strained GaInAs on GaAs. Properties of strained GaInAs on InP have also been studied. A first attempt to grow and fabricate a laser on InP has been successful, thus opening the opportunity to investigate strained lasers on InP. A first look into the theoretical properties of strained quantum wells has begun.

Strained Layer GaInAs Single Quantum Well Graded Index Separate Confinement Heterostructure (GRINSCH) Lasers

Review

Lattice mismatched heteroepitaxy is of great interest since it provides increased flexibility for band gap engineering. Strained-layer quantum wells have been used to control the band gap of the active region of semiconductor lasers,[1,2,3,4] thereby permitting lasing at previously unattainable wavelengths and allowing optical pumping of solid state glass lasers, for example. Moreover, recent studies have confirmed a splitting of the valence bands leading to a reduction in the hole mass parallel to the junction in the strained GaAs-GaxIn1-xAs-GaAs quantum well.[5,6] Theoretical studies predict that the lower density of states in the light hole band would allow the population inversion needed for lasing to occur at lower threshold currents for strained-layer lasers.[7,8,9] These lower threshold currents would lead to an increase in high speed performance over lasers made from unstrained material.[9] In the first series of design, growth, fabrication and measurement of strained-layer graded-index separate-confinement heterostructure (GRINSCH) single quantum well (SQW) lasers improvement over unstrained structures was clearly demonstrated.

In the last report, very low threshold current densities were obtained for strained single layer quantum well lasers compared to GaAs quantum well lasers. The low currents were the result of improved valence band properties and high quality material. These low threshold currents are believed to be due to a separate optimization of the growth conditions for the AlxGa1-xAs, GaInAs and the interface between them. The growth conditions for the quantum well were selected as a result of previous studies that evaluated the growth conditions for strained-layer GaInAs on GaAs.[10,11] Growth was stopped for 2 minutes before the 10 Å GaAs layer in order to obtain a smooth interface and allow for the substrate temperature to stabilize. The GaInAs quantum well was grown at the relatively low temperature of 500 °C to prevent the indium from either segregating or 'riding' the growing interface. Substrate temperatures higher than 500°C are not possible due to the problem of Indium segregation mentioned above, and due to evaporation of In at these growth temperatures above congruent sublimination.

An upper limit of 500°C substrate temperature suggests that improved GaInAs strained quantum well properties can only be sought through investigation of lower substrate temperatures. This study has been performed and is described in this report. Following the experiments to assess quality of strained quantum wells as a function of temperature, similar experiments were performed for strained GaInAs quantum wells on InP substrates for eventual application in strained lasers.

Strained GaInAs Quantum Well Growth Condition Study

Strained GaInAs quantum wells on GaAs substrates

Since previous studies clearly show the need to avoid substrate temperatures above 500°C, an investigation of properties of quantum wells grown at lower temperatures was conducted. Lower substrate temperatures would be desirable to permit wider latitude in setting substrate temperature with loosened accuracy, and would be important for eventual use of Be as p-type doping in the wells for laser applications since Be is known to diffuse at higher substrate temperatures.

Materials properties of strained GaInAs

Theory

The theoretical emission energy for GaAs clad strained GaInAs quantum wells is seen in Figure 1. The shape of conduction and valence bands of strained GaInAs have been taken from the literature. The light mass of holes in the region of about .050 eV depth into the valence band of strained In,GaAs quantum wells grown on GaAs is of great interest. Professor Brian K. Ridley will be in residence at Cornell for three months in early 1990 initiating the theory of such structures. He will return for two months for each of the next three years. He will submit a paper, for publication, entitled: "The In-Plane Effective

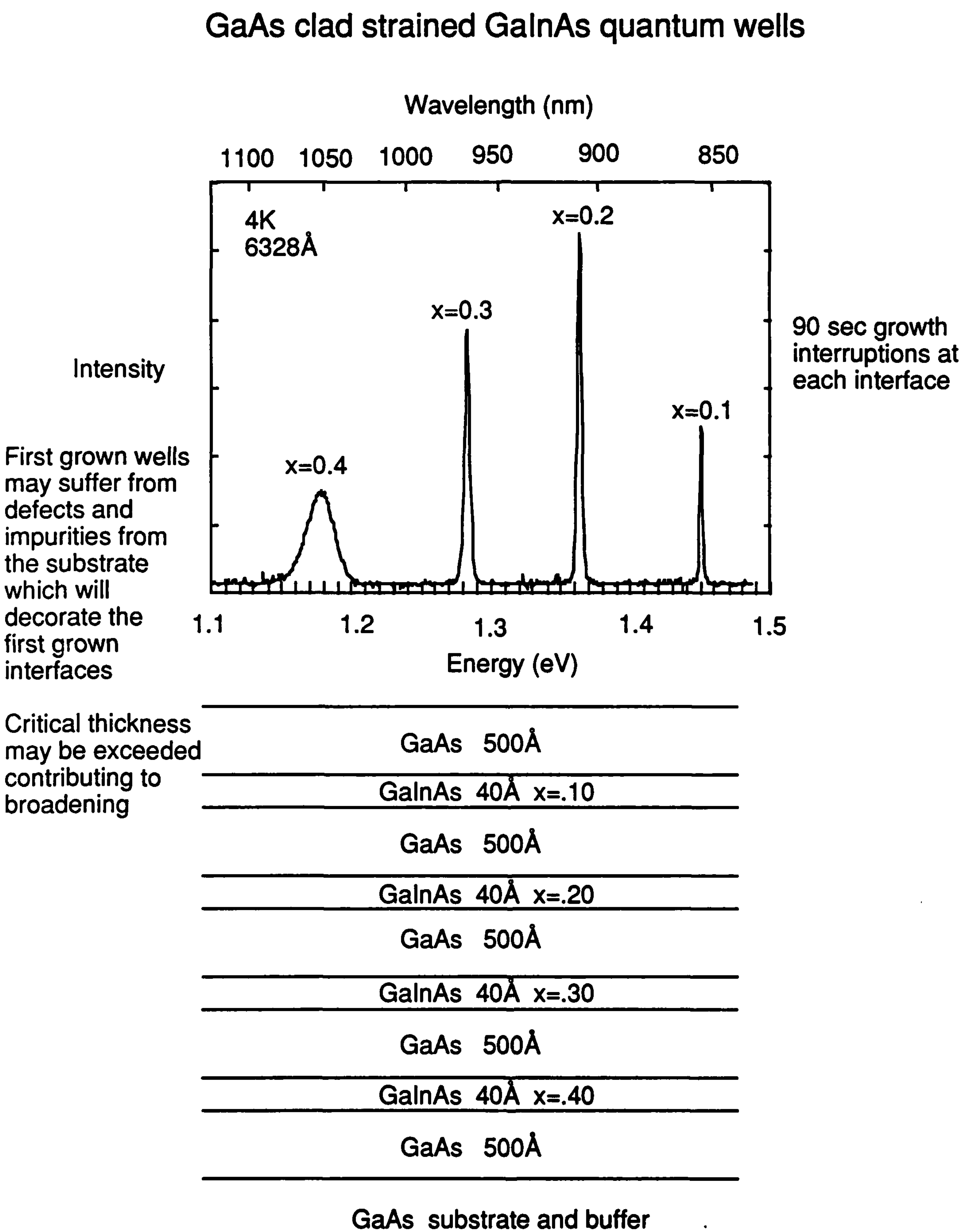


Figure 1. Quantum well characterization structure and 4K photoluminescence.

Mass in Strained-Layer Quantum Wells". The abstract of the paper is presented below. In the future, the results of this theory will be the key to the theoretical development on this program.

> The problem of calculating the valence band structure of strained-layer quantum wells in the effective mass approximation is reviewed. Using the spherical approximation and exploiting the simplicity of the infinitely-deep well model we show that the in-plane effective mass is determined by two factors - a splitting contribution which is dominant at large strains, and a quantum confinement contribution. A model for finite-depth wells is presented which gives analytic expressions for the zone-centre in-plane mass and associated non-parabolicity factor, and it is applied to the system $In_xGa_{1-x}As/GaAs$. The model allows the computation of valence band structure using no more than a pocket calculator. It is shown to give results in reasonable agreement with experiment.

Experiment

The growth of strained GaInAs on GaAs has been studied by low temperature photoluminescence (PL). A structure has been developed which permits evaluation of four different In mole fractions in a single growth. Four quantum wells (QW) of strained GaInAs clad by GaAs have been arranged to observe the PL from each, avoiding absorption of emission from the lower wells by the wells near the surface. This structure and a typical PL spectrum is seen in Figure 2. The emission from each well is distinctly resolved, and is found to take place at wavelengths which we have been theoretically predicted. Intensity comparisons are difficult to quantify as the wells closer to the surface have poorer quantum confinement, and those deeper are subject to less optical excitation due to absorption of the incident laser excitation in the layers above. The widths of the emissions are dominated by the random alloy fluctuations in the ternary quantum well material.

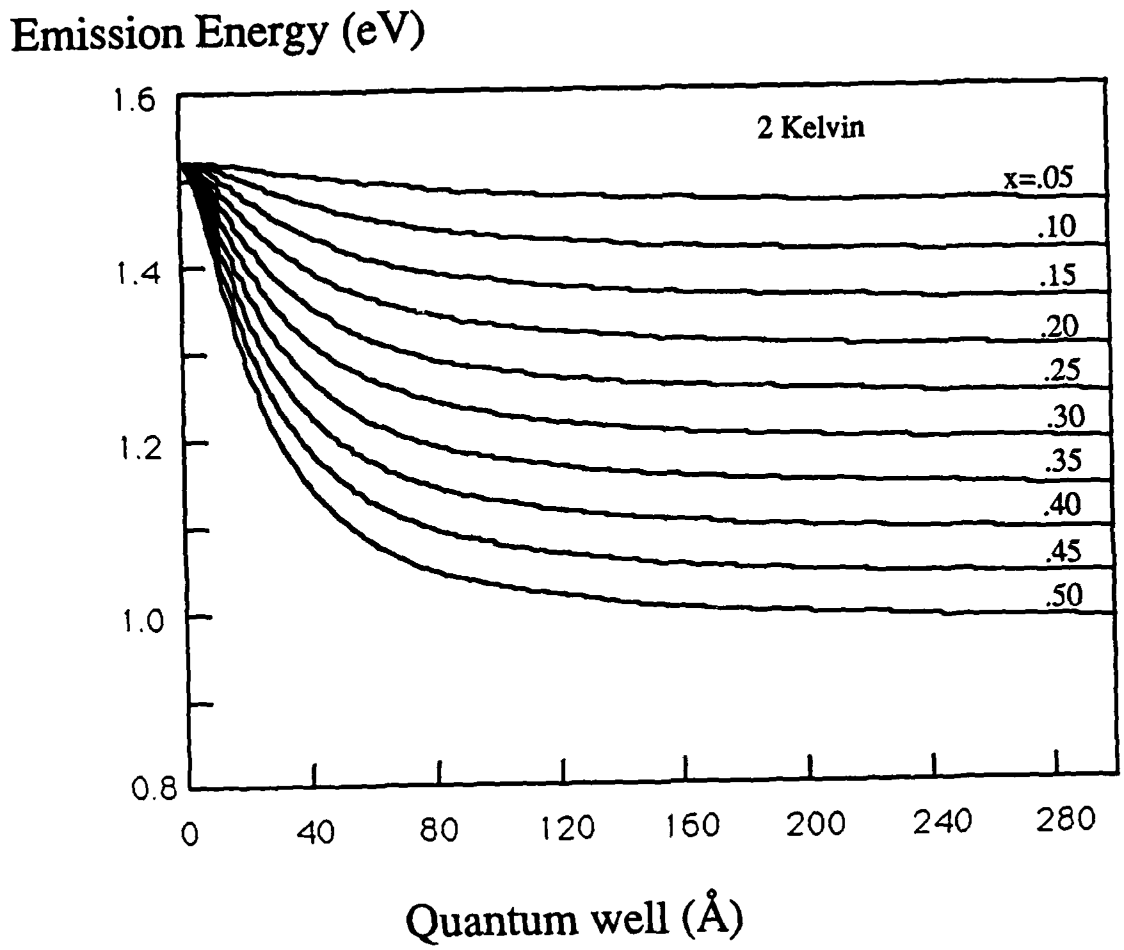


Figure 2. Theoretical quantum well emission energies for strained GaInAs/GaAs quantum wells.

To study the effect of growth conditions on QW properties, substrate temperatures have been varied from 300°C to 500°C. The PL intensity from the wells is a strong function of substrate temperature. A typical comparison of quantum well PL is seen in Figure 3. The best luminescence intensities are from wells grown at 500°C. Intensities fall as a function of growth temperature which is discussed later in this report. These structures are thin, and therefore subject to short growth times at moderate temperatures. In order to study the effect of growing strained quantum wells for laser applications, where substrate temperatures rise to over 700°C following the growth of the quantum well, these structures have been subjected to high temperature anneals.

Post growth annealing has been performed and intensities of the quantum well peaks has increased with annealing for quantum wells grown at all temperatures. The change in PL intensity for the QW with 30% In mole fraction is seen in Figure 4. The most improvement in intensity is seen for wells grown at low substrate temperatures. The intensities of the as-grown structures are degraded, presumably through non-radiative recombination in the strained GaInAs wells. The improvement is thought to come from the elimination of small densities of defects which arise at lower growth temperatures as the result of impaired surface mobility of the group III atoms. Additional energy provided by annealing permits these defects to be reduced in density.

The emission energies are not altered as a function of annealing, except for the 350°C grown layers. Figure 5 shows the PL from quantum wells grown at different substrates and annealed at 900°C. In the case of the very poorest quality quantum wells, grown at 350°C, the vacancy concentration is likely to be so high as to provide the driving force for interdiffusion of GaInAs into GaAs, thus altering the structure of the wells, and hence, the emission energy. The other quantum wells show no shift in emission energy as a result of annealing. This behavior is interpreted to mean that there is no interdiffusion of GaInAs into the GaAs clad layers. The quantum wells are structurally stable under these anneal conditions.

This stability is important to the growth of high quality lasers. A P-type AlGaAs cladding layer is grown after the GaInAs strained quantum well at 710°C. The strained quantum well cannot be altered during this high temperature growth if the benefits of strain on laser performance is to be

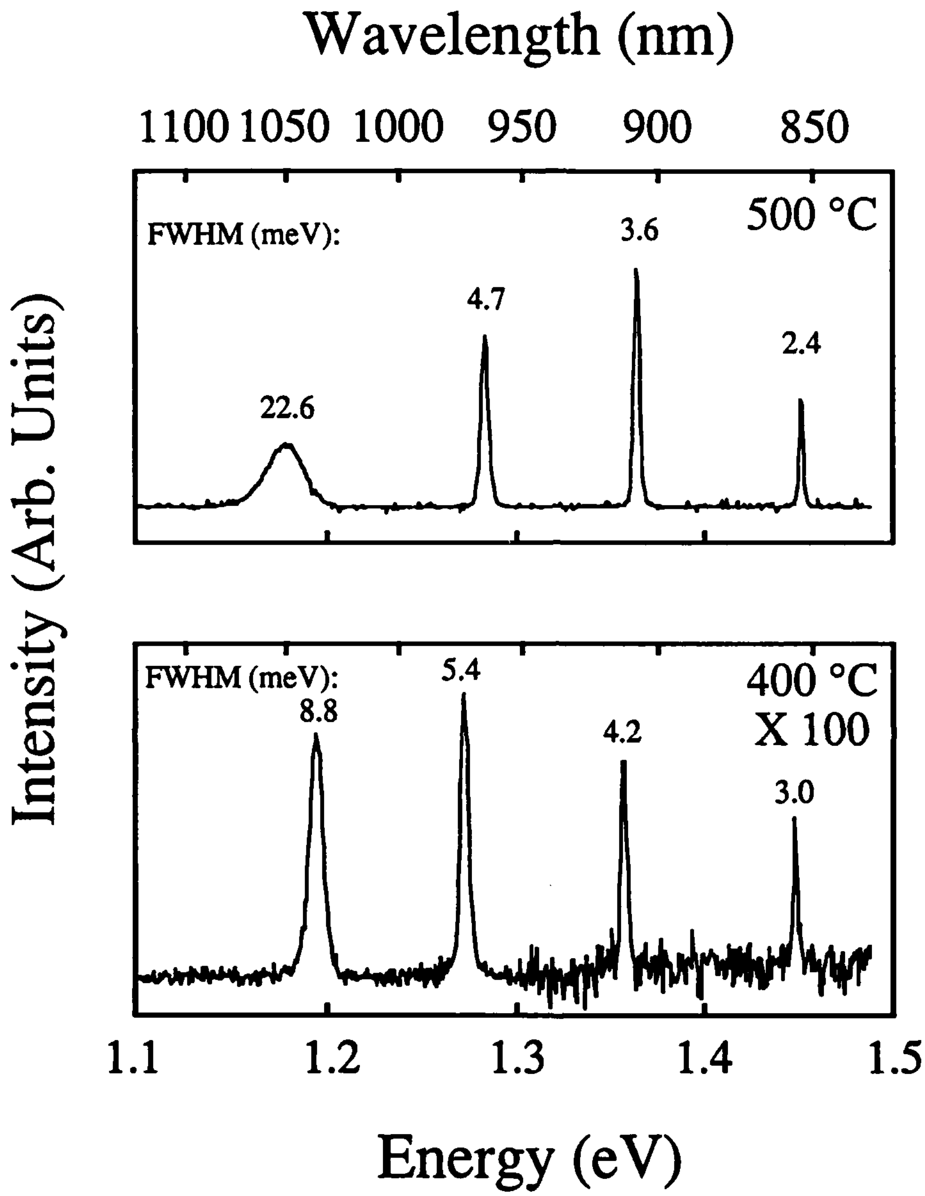


Figure 3. Quantum well 4K photoluminescence for structures grown at 500°C and 400°C.

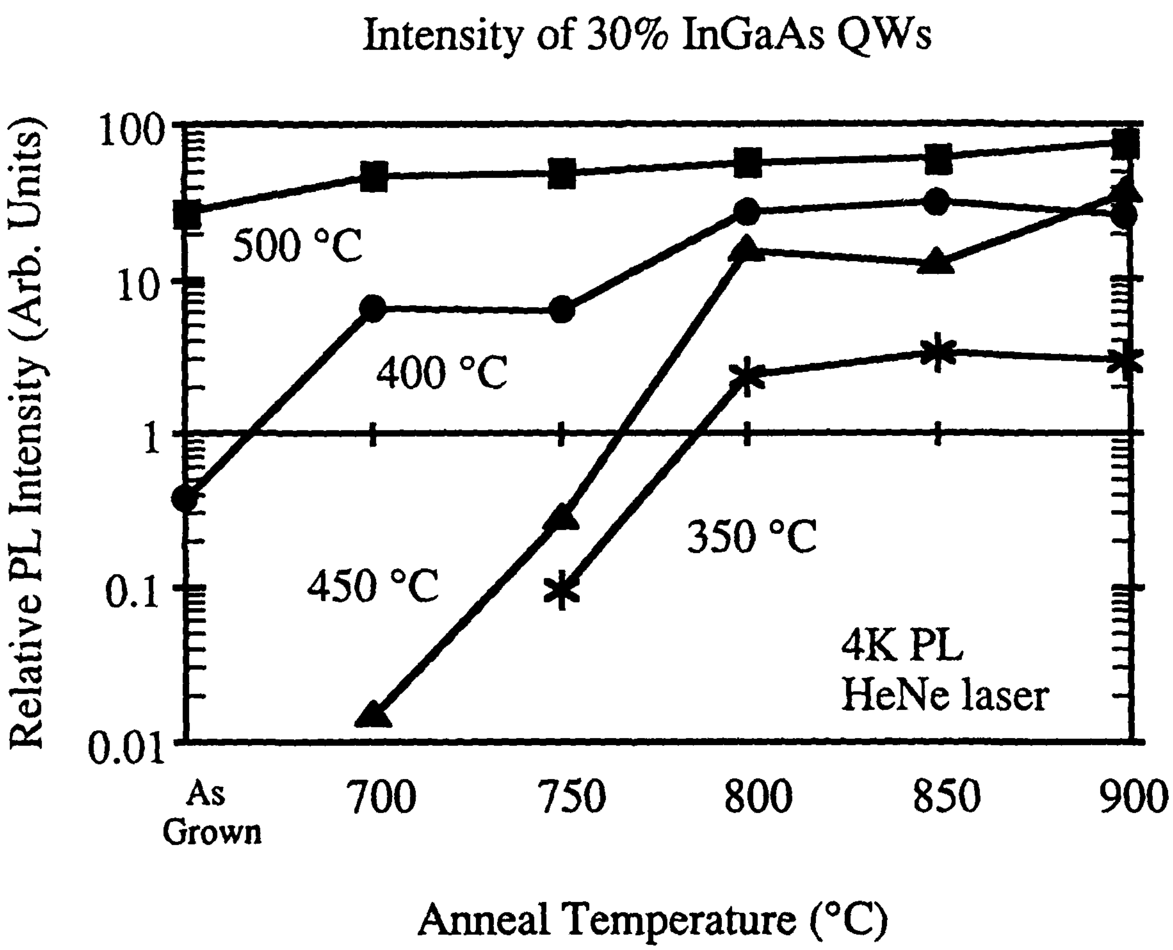


Figure 4. Quantum well 4K photoluminescence intensities as a function of annealing temperatures.

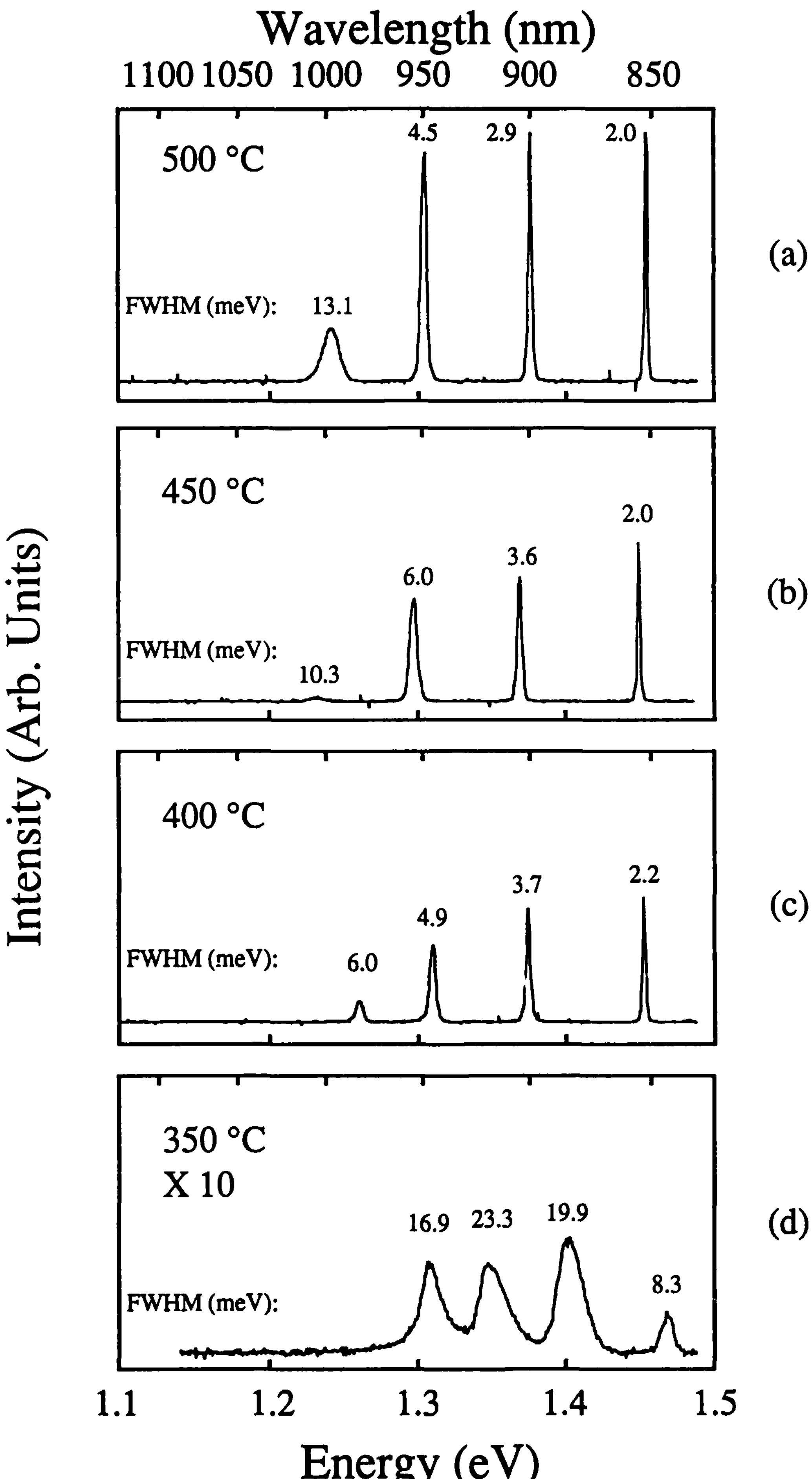


Figure 5. Quantum well PL as a function of annealing for structures grown at different substrate temperatures.

preserved. The annealing study shows that the structural stability is preserved because no emission shift occurs during anneal. Laser emission wavelengths agree with theory which further demonstrates stability of the quantum well to high temperature conditions.

The slight improvement in intensity of the strained quantum wells grown at 500°C, as a result of annealing, indicates that high temperature clad layer growth probably provides additional improvement in the quantum well radiative recombination efficiency. The best intensities are assumed to represent the growth, and anneal conditions, which would be expected to produce laser devices which would have the best performance. The lowest possible non-radiative recombination will lead to lowest laser thresholds and highest quantum efficiencies. The conclusion of the quantum well study is that the growth conditions which result in best quantum well emission intensity are similar to growth conditions first used in our growth of strained layer lasers. The tolerances in growth can probably be safely expanded to accommodate errors in substrate temperature which are on the low side of 500°C because the annealing of the quantum well during clad layer growth can improve the luminescence intensity.

Multiple strained quantum wells of single compositions and thin barriers have been grown to study their properties for application to lasers. They are being evaluated by low temperature PL and transmission electron microscopy (TEM). This work is ongoing.

Strained GaInAs quantum wells on InP substrates

Strained GaInAs quantum wells with AlInAs and AlGaInAs barriers have been grown on InP to study their properties for application to lasers. Theoretical predictions are for further improvement in threshold current densities and modulation bandwidths for these materials. The longer wavelengths possible would also permit reaching low loss fiber applications at 1.55μm, or use in eye-safe range finding applications. The quantum wells were evaluated by low temperature PL. Critical thicknesses were studied for this material system. Lasers using these strained wells were fabricated.

Strained GaInAs quantum wells with AlInAs barriers in InP substrates were grown to be studied in the same fashion as those on GaAs substrates described above. The goal of these growths was to see if it is possible to obtain the same high quality strained quantum well performance as obtained on GaAs substrates. A typical structure and 4K PL spectrum is seen in Figure 6. Each well is seen to exhibit strong luminescence. Intensity comparisons are difficult to quantify as the wells closer to the surface have poorer quantum confinement, and those deeper are subject to less optical excitation due to absorption of the incident laser excitation in the layers above. The widths are broadened by random alloy fluctuations in the well and barrier materials.

Variations on this structure were performed in order to experimentally determine critical layer thicknesses in this material system. Structures with different quantum well thicknesses, or different compositions were grown and evaluated by PL. A summary of these results is seen in Figure 7. A theoretical calculation of critical thickness for three different boundary conditions has been performed using the elastic constants of AlInAs as barrier material. The critical thickness for the structures studied appears to be smaller than theory would predict. This discrepancy is the result of either incorrect stiffness coefficients, or the model for critical thickness, or due to growth conditions which result in defect generation prior to the critical thickness which could be obtained under different growth conditions. More study is needed.

Graded index regions surrounding quantum wells for lasers are required for the best laser performance possible. In order to employ graded index structures in strained GaInAs lasers on InP substrates, it is necessary to know whether quaternary AlGaInAs is suitable as a barrier material. Quantum wells with AlGaInAs barriers as substitutes for AlInAs barriers were grown for PL characterization as performed above. The structures and PL measurements are shown in Figure 8. Emission is seen from all four quantum wells. Each has linewidths comparable to those for the ternary barriers. The absorption of the excitation laser is even stronger in the lower bandgap AlGaInAs than for AlInAs which results in lower intensity emission seen from the deeper wells. The quality seems to be good enough to apply to laser applications.

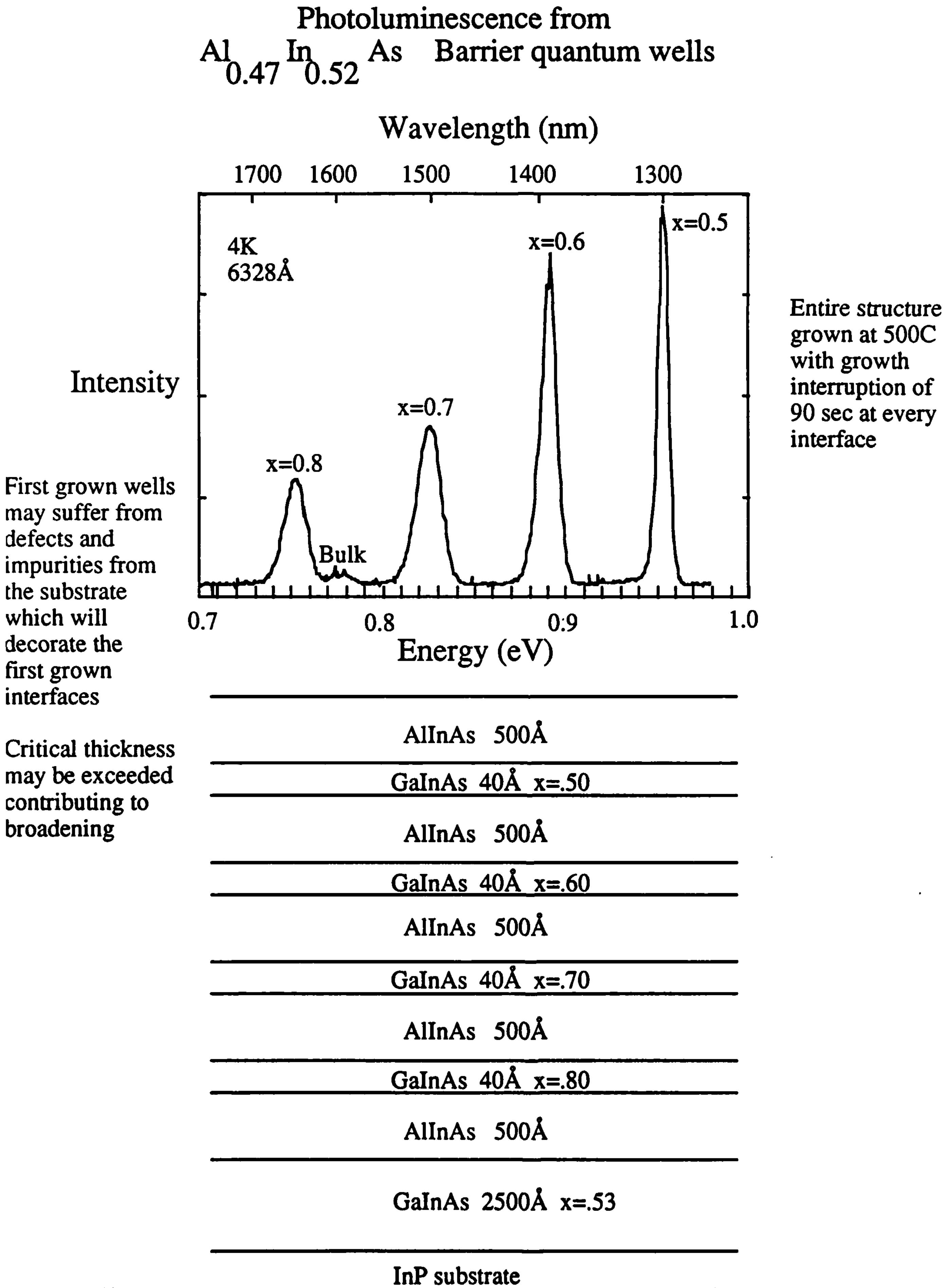


Figure 6. Structure and emission from strained GaInAs/AlInAs quantum wells on InP substrate.

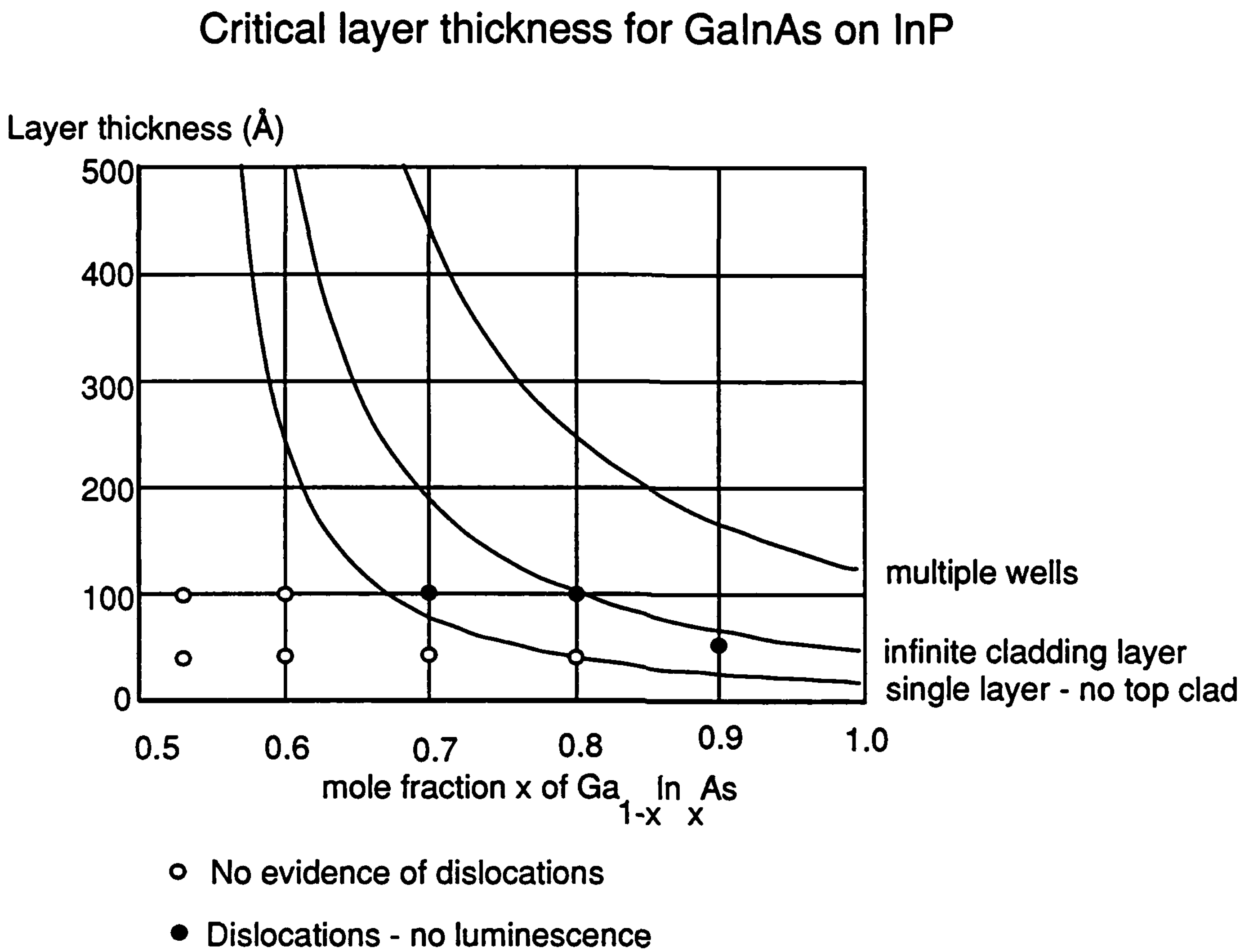


Figure 7. Critical thickness for strained GaInAs clad by AlInAs on InP substrates. Data points are from PL measurements.

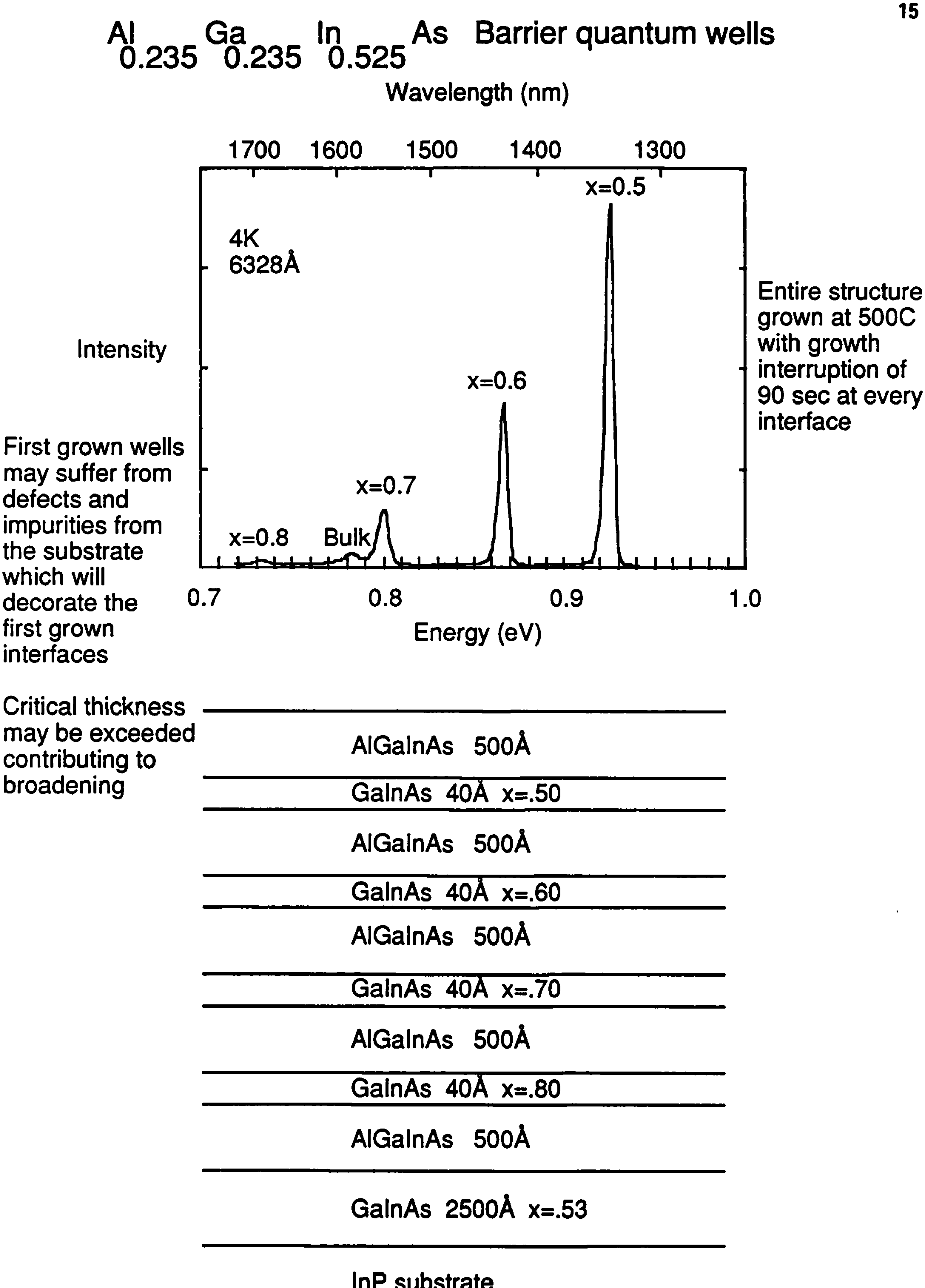


Figure 8. Structure and emission from strained AlGaInAs/AlInAs quantum wells on an InP substrate.

A laser on InP was fabricated. The structure is shown in Figure 9. The same high speed probing geometry used previously was employed. The optical output power versus pulsed current is seen in Figure 10. The threshold density for this device is high - over 2000 A/cm^2. The optical spectrum of the laser is seen in Figure 11. Emission at 1.46μm is in agreement with predictions for this structure. The poor threshold is thought to be the result of non-optimized growth conditions. More lasers will be grown and processed and reported in the next report.

TEM

TEM characterization of strained GaInAs/GaAs layers has been performed and is described in a separate appendix to this report.

Technology Transfer from Work Under this Grant to Date

See the last report for technology transfer from work performed under this grant to date. No new transfer is reported during this period.

Ongoing Research, Near Future Plans

Completion of the study of growth conditions of strained GaInAs/GaAs quantum wells will occur in 1990. Research into strained layer AlInAs/GaInAs/InP quantum wells will continue. Lasers will be fabricated in this material system. The goal of these devices is to further improve laser performance due to valence band modification of strained layer GaInAs on InP which will offer valence band structure with better properties than strained GaInAs on GaAs. The lasing wavelengths will also be more valuable for 1.55μm fiber applications.

Multiple QW GaInAs/GaAs lasers will be explored to determine their suitability to short cavity length devices. Superior high frequency performance is the goal of this effort. Portions of

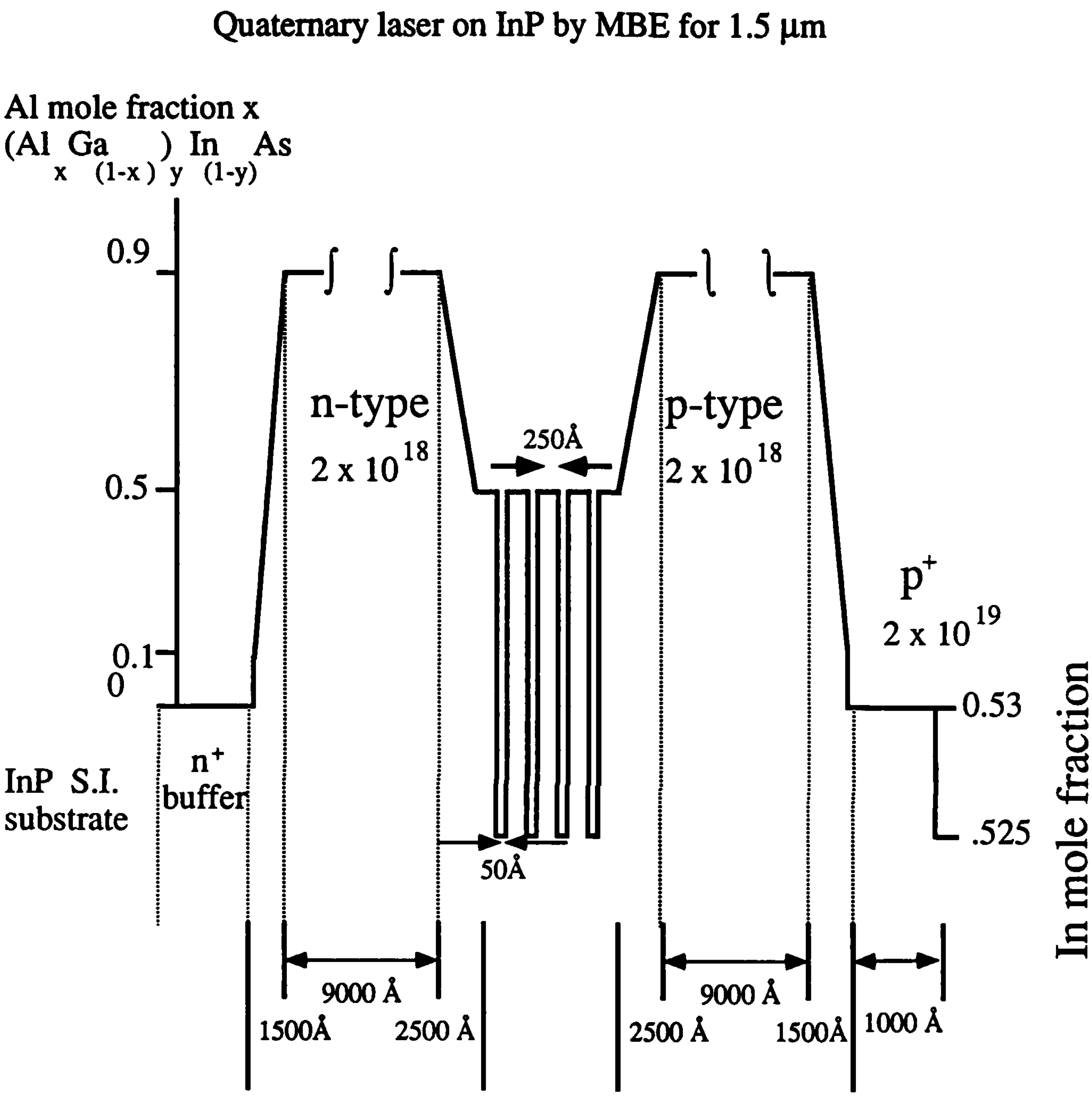


Figure 9. Structure of laser on InP substrate.

GRINSCH Laser on InP

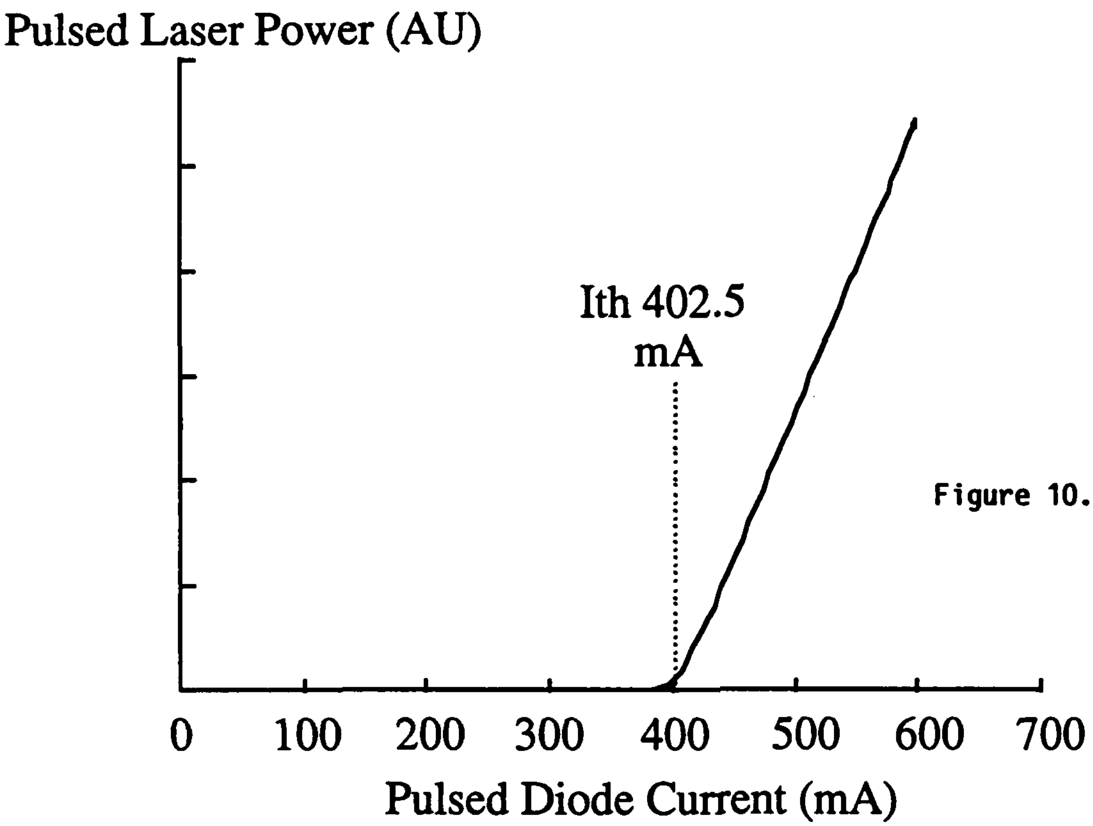


Figure 10. Optical power versus current for laser on InP substrate.

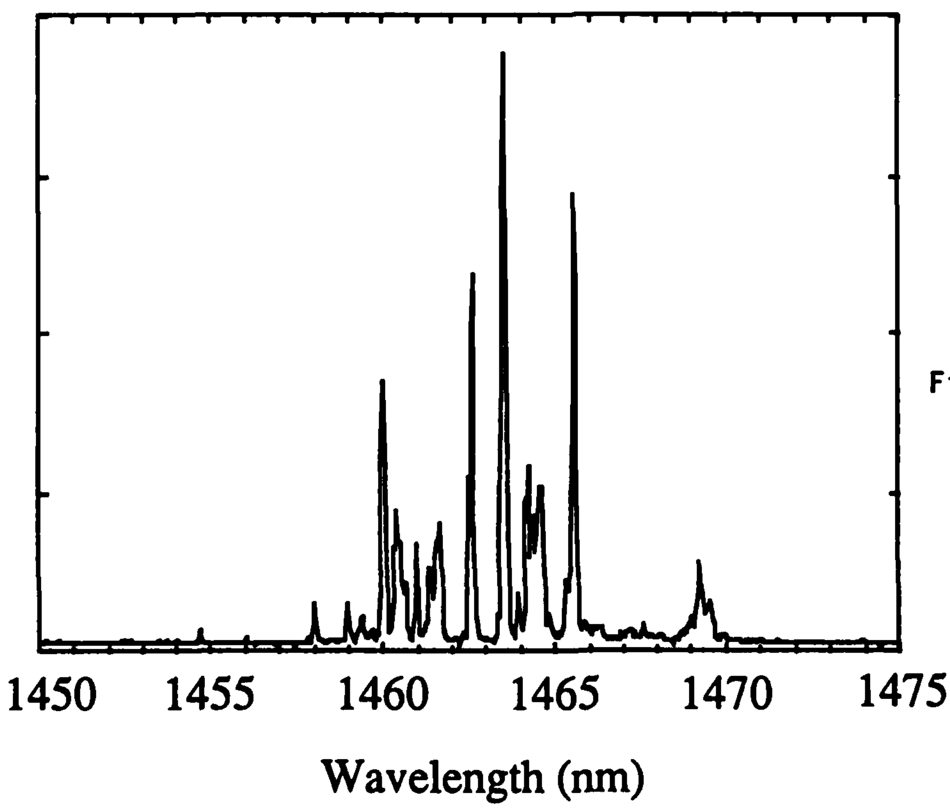


Figure 11. Optical spectru for laser on InP substrate.

laser materials fabricated under this grant will be supplied to an ongoing program by GE at Cornell to fabricate dry etched laser mirrors for short cavity length applications.

Papers and Presentations Supported by this Grant During This 6 Months

1. "Comparison of Vacuum and Semiconductor Field Effect Transistor Performance Limits", L.F. Eastman, 2nd International Conference on Vacuum Microelectronics, Bath, England, (July 24-26, 1989); IOP Conf. Ser. No. 99, Section 7, 189-194 (1989).

2. "RF and DC Characterization of P-Channel AlGaAs/GaAs MODFET's with Gate Lengths as Small as 0.25 mm", H. Park, P. Mandeville, R. Saito, P.J. Tasker, W.J. Schaff and L.F. Eastman, 12th IEEE/Cornell Conference on'Advanced Concepts in High Speed Semiconductor Devices and Circuits', Cornell University (Aug. 7-9, 1989) 101-110.

3. "Optical and Microwave Performance of GaAs-AlGaAs and Strained Layer InGaAs-GaAs-AlGaAs Graded Index Separate Confinement Heterostructure Single Quantum Well Lasers", S.D. Offsey, W.J. Schaff, P.J. Tasker, W.D. Braddock and L.F. Eastman, 12th IEEE/Cornell Conference on'Advanced Concepts in High Speed Semiconductor Devices and Circuits', Cornell University (Aug. 7-9, 1989) 329-339.

4. "Optical and Microwave Performance of GaAs-AlGaAs and Strained Layer InGaAs-GaAs-AlGaAs Graded Index Separate Confinement Heterostructure Single Quantum Well Lasers", S. D. Offsey, W.J. Schaff, P.J. Tasker and L.F. Eastman, Prosus presentation - National Nanofabrication Facility, Cornell University, (Oct. 9-10, 1989).

1. W. D. Laidig, Y. F. Lin, P. J. Caldwell, J. Appl. Phys. **57**, 33 (1985).
2. D. Feketa, K. T. Chan, J. M. Ballantyne, and L. F. Eastman, Appl. Phys. Lett. **49**, 1659 (1986)
3. S. E. Fischer, D. Fekete, G. B. Feak, and J. M. Ballantyne. Appl. Phys. Lett. **50**, 714, (1987)
4. R. M. Kolbas, N. G. Anderson, W. D. Laidig, Y. Sin, Y. C. Lo, K. Y. Hsieh, and Y. J. Yang. IEEE J. Quantum Electron. **QE-24**, 1605 (1988)
5. J. Hwang, C. K. Shih, P. Pianetta, G. D. Kubiak, R. H. Stulen, L. R. Dawson, Y. C. Pao, and J. S. Harris. Appl. Phys. Lett. **52**, 308 (1988)
6. E. D. Jones, S. K. Lyo, J. F. Klem, J. E. Schirber, C. P. Tigges. Proc. Inst. Phys. Conf. Ser. vol. **96** (1989)
7. A. R. Adams. Electron. Lett. **22** , 250 (1986)
8. E. Yablonovitch, E. O. Kane. J. of Lightwave Tech. **LT-4**, 504 (1986), see also correction J. of Lightwave Tech. **LT-4**, 961 (1986)
9. I. Suemune, L. A. Coldren, M. Yamanishi, and Y. Kan. Appl. Phys. Lett. **53**, 1378 (1978)
10. W. J. Schaff, L. F. Eastman. European MRS Proceedings, **Vol. XVI**, 295 (1987)
11. D. C. Radulescu, W. J. Schaff, L. F. Eastman, J. M. Ballingall, G. O. Ramseyer, S. D. Hersee. J. Vac. Sci. Tech. **B7**, 111 (1989)

APPENDIX

REPORT OF THE TEM INVESTIGATION OF LASER STRUCTURE-MATERIALS

A Report

for the Period December 15,1988 - December 14, 1989

C.B. Carter

MATERIALS SCIENCE AND ENGINEERING
Cornell University
BARD HALL
ITHACA, NEW YORK 14853, USA.

Report of the TEM Investigation of Laser Structure Materials

Introduction

Cross-section specimens were prepared from the various epilayers in the standard manner; slices of each wafer were epoxied together epilayer-to-epilayer and then ground, polished and dimpled to produce a thin area at the substrate-epilayer boundary. The samples were then ion-milled to perforation at liquid nitrogen temperatures prior to examination in a JEOL 1200EX transmission electron microscope. The cross-sections were then typically examined in the dark-field mode, using the 200 reflection which is sensitive to differences in the chemical species present in the material.

1. Graded Layer Superlattice structures 3317-3320

TEM images from the cross-section specimens show the presence of uniformly smooth and flat layers in these specimens. Dark-field images taken using the 200 reflections, show these results particularly clearly. The thicknesses of the active layers was measured directly from the images and found to be close to the designed values in all cases (Figs. 1 and 2). The superlattice layers, which were designed to be repeating layers of 290Å $Al_xGa_{1-x}As$ and 10Å GaAs, were individually of uniform thickness, but the spacings were slightly variable from layer to layer. This is particularly obvious in the image of wafer 3318, where the separation of the superlattice layers becomes progressively smaller nearer to the active layer. Far from the active layer the spacing is ~230Å, but closer to the active layer the spacing is reduced to 150-200Å. This reduction of the superlattice period occurs on both sides of the active layer, i.e. both before and after growyh of the active layer. This effect is observed to some extent, in all the wafers studied. The graded superlattice, which is grown immediately adjacent to the active layer, shows this effect particularly strongly although the effect extends beyond this region. The graded superlattice appears to have a more variable period than the uniform superlattice, and is slightly thinner than the designed value of 2500Å. The thickness of these graded layers were measured to be 1500Å, 2000Å and 2000Å (all ±10%) for wafers 3318, 3319 and 3320 respectively. Only in wafer 3320, which contained layers with the the highest indium content, were any dislocations observed. In this case a few dislocations were observed emanating from the upper side of the active layer at isolated points along the length of active layer.

2. Graded Layer Superlattice Structure 3132

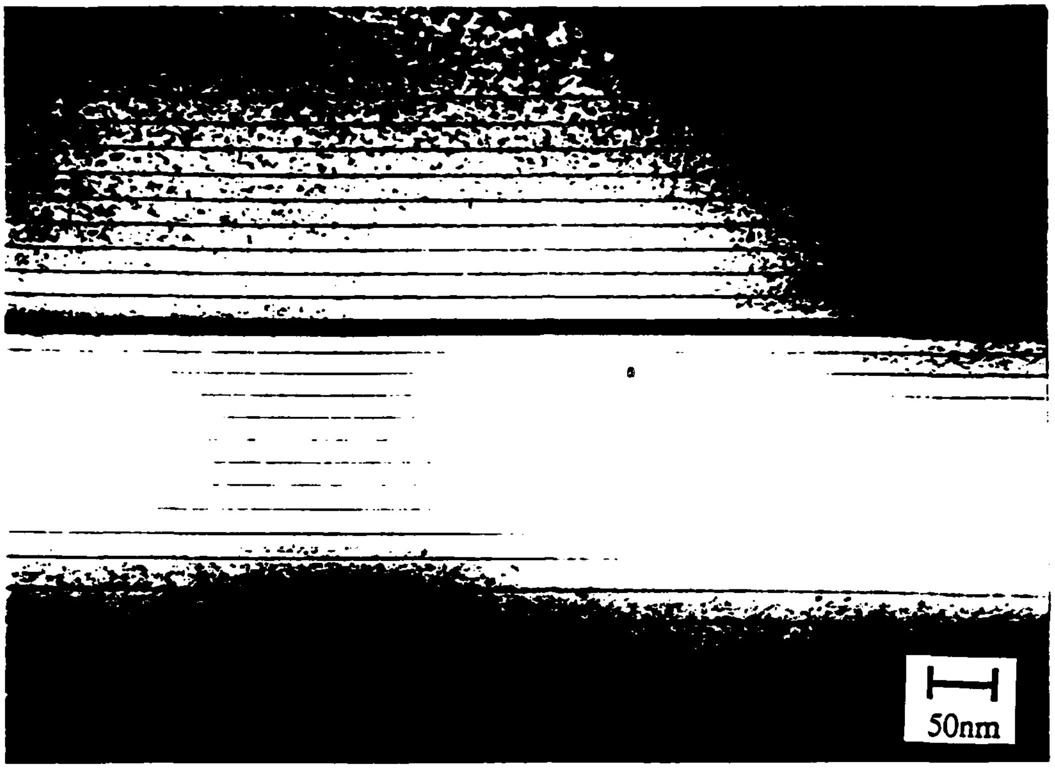
Optical micrographs from the surface of this wafer show ridges under Normarski illumination conditions, which are particularly pronounced at the wafer edge (Fig. 3). The sample available for examination originated from the extreme edge of the wafer. TEM images from this sample showed some surprising features. In cross sections from different parts of the wafer viewed along the [110] and [1$\bar{1}$0] directions showed different morphologies. In one direction the superlattice layers appeared uniformly smooth and flat, the active layer, however, appeared slightly uneven. In the specimen prepared in the orthogonal direction, the superlattice layers developed a strongly facetted morphology at about the point where the grading of the superlattice composition begins (Figs 4). The active layer and the top graded layer varied in thickness which resulted in a 'smoothing out' of this faceting, and the final upper superlattice is relatively smooth and flat. The width of the active layer and its local orientation, therefore, varies widely. High-resolution images from this sample show that the active layer is inclined to the (001) growth plane by 3° or 4° (Fig. 5). The interfaces between the well and the barriers appear to extend over several atomic layers.

3. Critical Thickness Layers 3487 3488

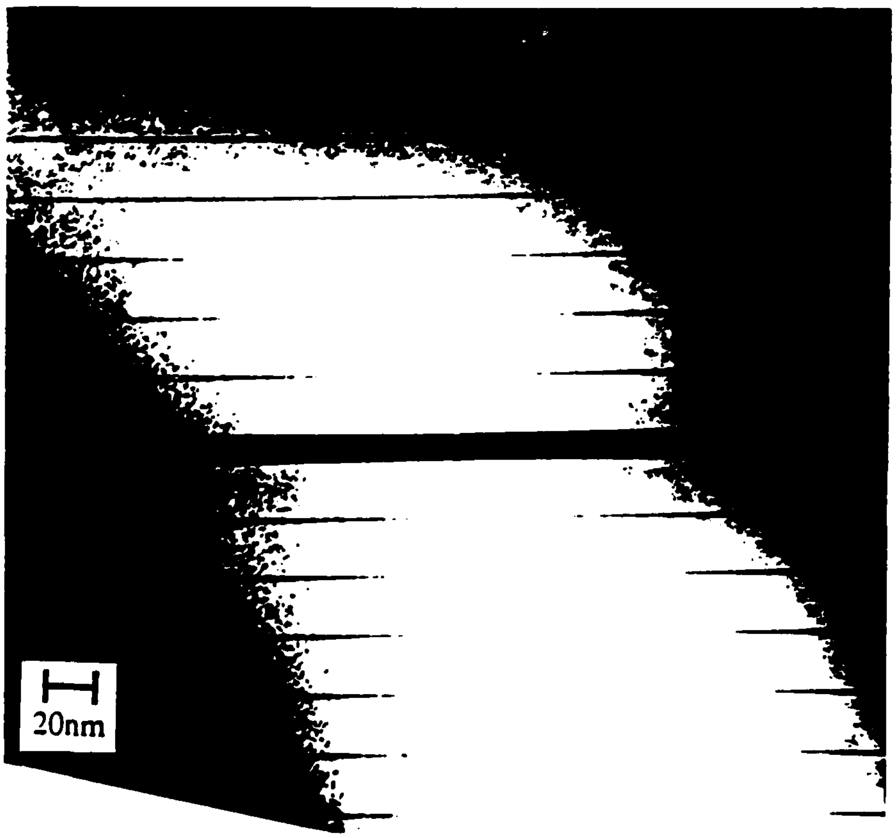
Two specimens were examined which contained four quantum wells of equal thickness and different indium concentrations, corresponding to well thicknesses up to the theoretical critical thickness. In both cases the lower two wells were grown with good crystallinity, the third well was observed to contain many stacking-faults and micro-twins, which propagated out into the subsequent layers (Fig. 6). The fourth well also contained large numbers of additional faults. The width of the wells was measured to be ~55Å and their separation was ~900Å. The presence of strong bend contours around these wells indicates that a large amount of stress is present in the epilayers. The lower two wells are sharp, flat and appear to be strain-free.

4. Indium Phosphide based Quantum Wells 3505

The wells visible in the 200 dark-field images were uniformly smooth and flat (Fig. 7) indicating a good quality growth. The interfaces between the wells and the barriers appears to be very sharply defined. In images of extended areas of the sample no defects were seen.



Wafer 3318 200 Dark-field image, showing the reduction in spacing of the superlattice layers in the graded region



Wafer 3319 200 Dark-field image. Note the lighter region above the active layer

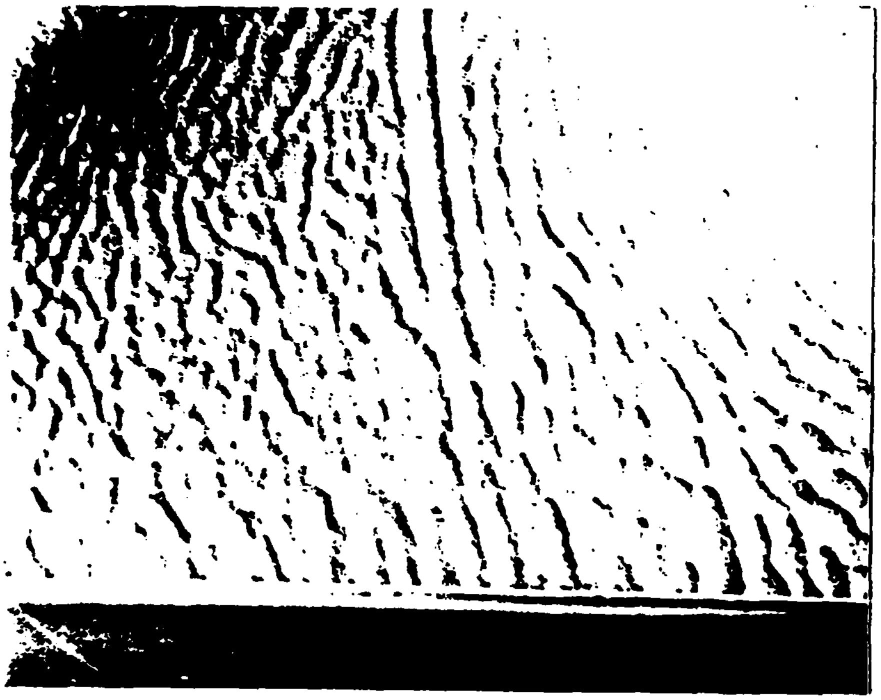
Figure 1

Wafer 3320

200 Dark-field images showing dislocations emerging from the upper surface of the active layer

Figure 2

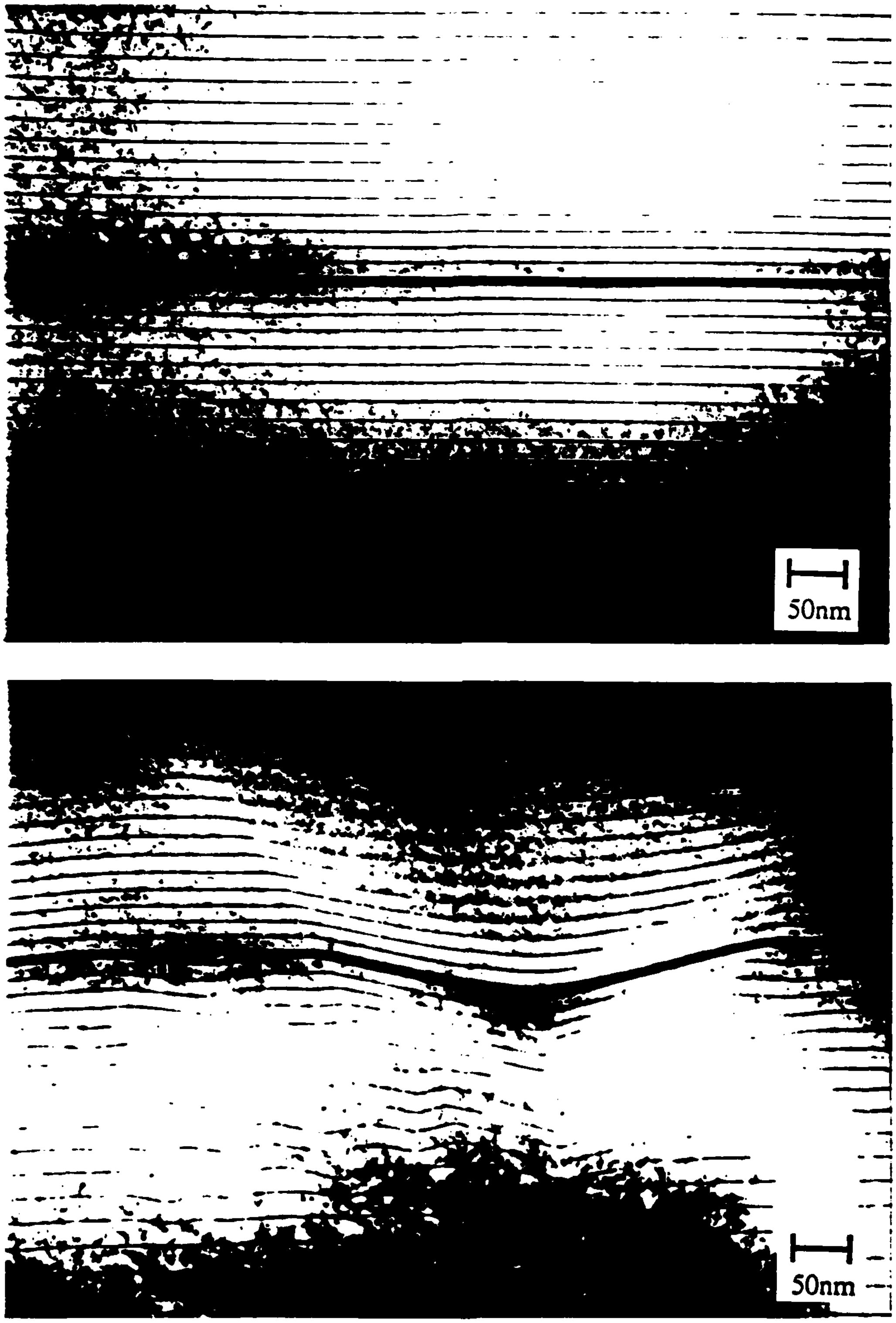
Wafer 3132



Optical micrograph showing strong Normarski contrast from the surface of the wafer. Image obtained near the edge of the wafer. 50X magnification

Figure 3

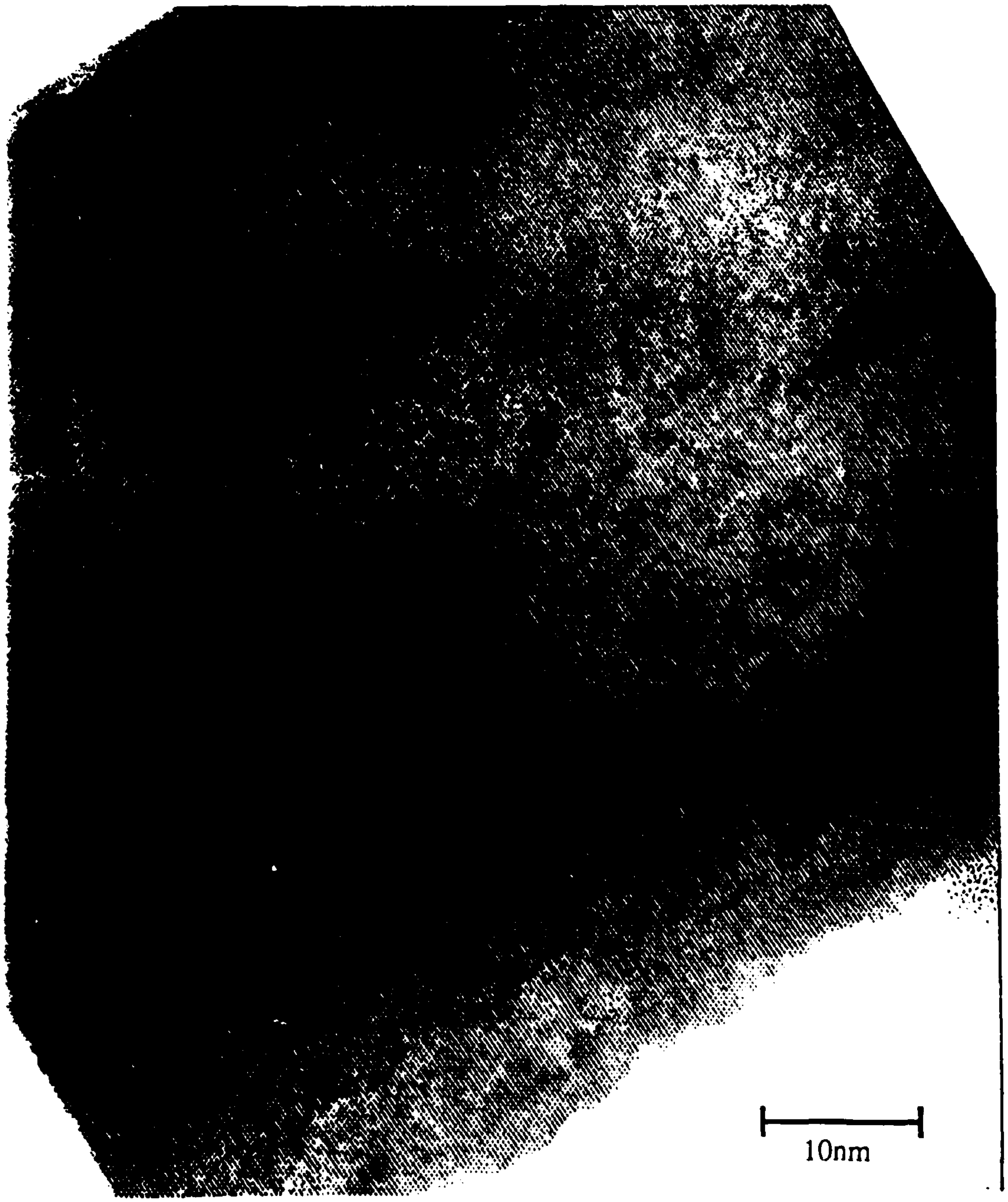
Wafer 3132



200 Dark-field images in orthogonal <110> directions Note the facetting of the layers in the graded layer region.

Figure 4

Wafer 3132



High-Resolution lattice image from the active layer

Figure 5

Wafer 3487 200 Dark-field image. Note the break-up of the structure at the third quantum well

Wafer 3488 200 Dark-field image. Note the break-up of the structure at the third quantum well

Figure 6

Wafer 3505

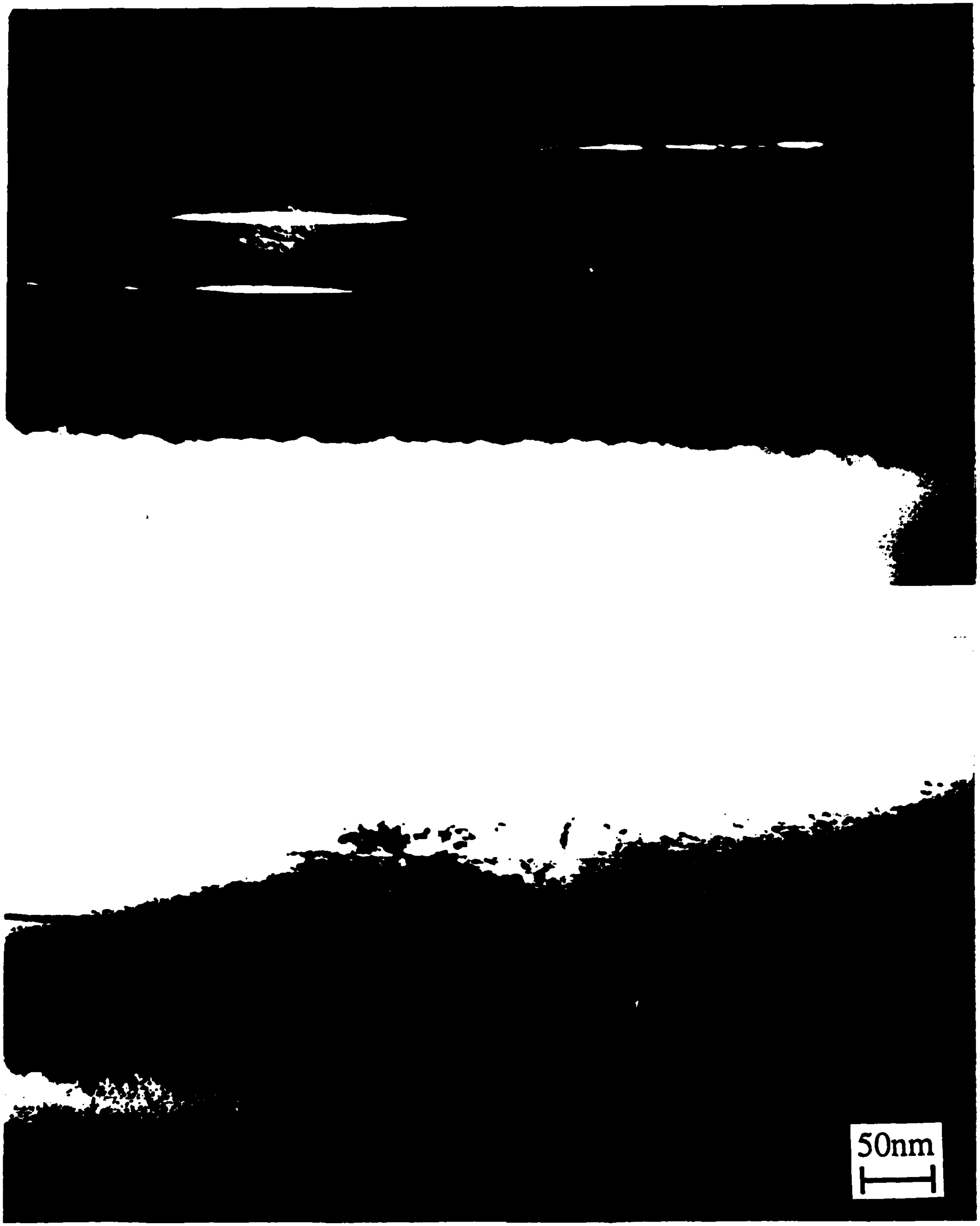


Figure 7

Wafer 3505

Bright-field image showing extended area of epilayer with no crystal defects.

Figure 8